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Review of Fracture Control Technology

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This report is a review of the methodology currently used for application of fracture control technology in the design, construction and operation of naval ships and submarines. Fracture control technology is defined as the coordinated technologies to deal with the phenomena of crack initiation, crack propagation and fracture, including effects of hostile environments and spectrum loading. A distinction is drawn between fracture control, as defined in this manner, and structural integrity, which involves all aspects of ship and submarine design, including all of the fitness for service considerations. There are essentially two non-competing approaches to prevention of
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cracking problems: (1) the safe-metal approach, which is used for most naval applications, depends on the inherent resistance of materials to crack initiation and growth to prevent serious problems, and (2) the analytical approach based in fracture mechanics provides the capability for detailed, analytical consideration of crack growth and structural failure when the application demands its use. Included in this report are a summary of the current Navy philosophy for applying either or both of the methodologies, an assessment of the problems inherent with each and recommendations for establishing formal fracture control plans when the application warrants their use.

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REVIEW OF FRACTURE CONTROL TECHNOLOGY IN THE NAVY

This report reviews past and current methods for control of crack initiation, crack growth and fracture in Navy ship and submarine structures. The efforts described are a part of a larger program sponsored by the Naval Sea Systems Command (Code 05R15) to advance the organization and application of Fracture Control Technology in the Navy. Fracture control technology includes the coordinated technologies for detailed consideration of crack initiation, crack propagation, and fracture on an analytical basis. A distinction is drawn between fracture control defined in this manner and structural integrity, which involves all aspects of ship and submarine design. The key difference is in the use of analytical methods of fracture control technology to solve specific problems or design specific structures or components as opposed to the all-inclusive approach to ship design embodied by structural integrity technology. By this definition, fracture control technology is a logical part of structural integrity technology and must be complementary rather than competitive. Fracture control technology has been pioneered and developed for approximately 30 years at all levels of Navy research and development in materials, structures, and design methodology. These efforts were and still are directed in large part at the solution of problems specific to developmental materials systems, e.g., HY-130, or to specific design or operational problems, e.g., PHM strut/foil system and submarine hull safety.

This review did not encompass all of the technical areas necessary to integrate crack initiation, crack growth and fracture technology into the design process. It was decided to exclude a detailed review of developments in technologies of loads, NDI and other factors and to concentrate efforts in the following areas:

- Review the history of the methods used by the Navy to prevent crack initiation, crack growth and fracture,

- Summarize the technical approaches currently used to control defects in Navy ships, submarines and machinery systems, and

- Identify the requirements and documentation necessary to implement detailed fracture control technology where needed and applicable.

HISTORY OF FRACTURE CONTROL METHODS IN THE NAVY

The fracture control methods currently practiced in the Navy have their earliest origins in the dramatic failures of the merchant fleet of Liberty Ships during the 1940's, where low fracture toughness of hull steels at operating

temperatures was commonly encountered.* The development of means to combat fracture is predominantly concerned with the hull structure of ships and submarines. Fracture had not been recognized as a major problem in ships prior to construction of hulls by welding, rather than riveting. Riveted joints provided a convenient crack arrest mechanism, and failure of an occasional plate was accepted without undue concern. By welding the entire ship hull, a continuous failure path was provided so that there were several occurrences of complete fracture of these ships. Most of the Liberty Ship fractures originated at small defects, which were introduced by welding. There are also recorded instances of welded ships having fairly large defects which did not cause failure. These can probably be attributed to either the varied quality of the steels used, so that a growing crack entering a tougher plate could be arrested, or the propagation of the crack into regions of compressive stress or low tensile stress.

Engineering Methods

Given the problem of fracture control of the entire fleet of Navy ships, the only feasible approach, both technically and economically, to control fracture was to provide adequate resistance of the hull steels to fracture. In the Navy, both surface ship and submarine hull steels, along with their associated fabrication processes, were selected or developed to provide sufficient resistance to fracture. Using principles developed by Pellini, the intent of the shipbuilding technology was to develop and procure materials and to fabricate structures that could resist catastrophic propagation of defects typically present in any welded structure under all foreseeable operating conditions or threats, including attack by underwater explosion.

The term "safe-metal" approach has been applied to this concept, which has served the Navy well for more than 30 years and has been refined by years of application. It was and still is next to impossible to predict operating loads with a high degree of precision for most ships because of the environment in which they must operate and because the hull structure must withstand underwater explosions. Past and current design philosophy is to build ships to a quality level as high as can be attained at a reasonable cost and to rely on proven design methods and the inherent properties of construction materials to prevent catastrophic fracture. The safe-metal approach effectively eliminates the need for large scale application of methods to predict the behavior of cracks since the properties of construction materials are high enough to contain them. The minimum requirement of this approach is to avoid brittle (plane-strain) conditions (possible fracture at elastic stresses) in any material thickness or at any stress level for the anticipated loading; high-strength materials (yield strength > 120 ksi), which are not efficient for ship construction, are also precluded from all except very specialized structures for this reason.

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*Because of the extensive literature available on this subject, detailed references are not used in this report. The more important contributions are listed in the Bibliography, Appendix B.

In summary, the safe-metal approach is employed for the design of the vast majority of ship structures and components. On a historical basis, the safe-metal approach has been the only feasible way, both technically and economically, to design, build and operate structures as large and complex as ships. Most problems that are encountered with this approach involve cost; these will be discussed in a later section of this report. Attempts to carry over the safe-metal approach into other areas of concern encompassed in fracture control technology – fatigue crack initiation and growth and stress-corrosion cracking – as well, have met with mixed results. Metals which have very high resistance to fracture are not always equally resistant to crack initiation and growth; these latter two crack growth mechanisms must be considered separately.

Analytical Methods

At the same time that the safe-metal approach was emerging, the technology of linear elastic fracture mechanics was also developing. Although the origins of fracture mechanics date to the early 1920's, engineering development and applications to structural design did not start in earnest until the pioneering efforts of Irwin and Kies in the 1950's and the formation of ASTM Committee E-24 on the subject in the early 1960's. Apart from the ability to accurately predict the initiation of brittle fracture, fracture mechanics concepts afford the designer the ability to handle crack propagation due to cyclic loads, and to some extent, to predict the severity of potential stress-corrosion crack growth. These latter two capabilities can be far more important to Navy designers than the fracture aspect, per se, since the safe-metal approach is predicated on eliminating the possibility of brittle fracture. The two methods of dealing with fracture can be viewed as the opposite ends of the spectrum of strength levels available in structural materials; linear elastic fracture concepts are strictly applicable for high-strength, low-toughness materials, while the safe-metal approach [nonlinear fracture mechanics] applies for low-strength, high-toughness materials. The transition between these two extremes is quite rapid as strength is varied; this transition is the region being approached by the introduction of new structural materials for the purpose of developing more efficient, light-weight structures and by the development of analytical methods that apply for crack growth and fracture in the presence of limited plasticity. To date, while linear elastic fracture mechanics has been used quite successfully to analyze crack growth in both low-strength and high-strength naval materials, the applicability of linear-elastic methods for analysis involving plasticity is very limited.

Current Status

Current Navy design practices incorporate the concepts defined under fracture control technology into the design process at appropriate places and consider fatigue, crack growth and fracture as one of many inputs to an all inclusive "Structural Integrity Plan." The background of experience gained in ship construction has yielded a thorough general knowledge of what works and what doesn't work, so that design manuals for details largely contain acceptable

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weld joint configurations and time-proven formulas to determine scantlings. As long as "forgiving" materials are used for ship construction, and structural weight does not become a driving factor, the safe-metal approach will continue to be quite adequate. At present, there is no compelling reason to introduce analytical methodology on a large scale. When problems requiring detailed analytical consideration of crack growth and fracture arise, as in the case of the PHM struts and foils, Navy specialists in the appropriate disciplines are required.

Submarine structures have led the way in fracture control, as practiced by the Navy. Because of the severe consequences of structural failure, more care in fabrication, inspection and maintenance is practiced for submarines than for surface ships, and the hull fabrication cost is accordingly higher than that for surface ships. Establishment of materials property criteria and qualification of suppliers of necessary product forms and fabrication processes to certify that the materials meet these standards is the first step and basically the essence of the safe-metal approach. Inspection of the fabricated structure for cracks and other defects at an inspection level commensurate with the application and follow-up inspections at regular intervals during the service life is the second step. These processes are necessary in any rigorously-applied method to prevent crack initiation, crack growth and fracture and they contribute significantly to the cost of many ship structures and other critical items. While these costs may be small in comparison to costs of other components, there is a general feeling that some reductions may be possible.

An exception to the safe-metal approach was necessary in the PHM project, wherein the required strength of the material for strut and foil construction (17-4 PH steel) dictated that plane strain conditions could be present for some thicknesses. In addition to potential failure by fracture, crack growth is also a primary concern in this application; these factors are critical for most of the strut/foil design. The PHM strut/foil remains the only surface ship structural system for which both minimum materials properties (dynamic tear energy and K_{Iscc}), and minimum service and periodic careful inspections were specified in the contract.

Some attempts to formalize the application of fracture control technology to Navy ships and submarines have been made. In 1973, an R&D based committee was formed to draw up a draft specification (1) modeled along the lines of the Air Force approach to Structural Integrity (MIL STD 1530), with the intent of exploring the applicability of an analytical approach to Structural Integrity for naval systems. The consensus of the Navy technical community was that such a document was premature in that the approach taken required technology for analytical treatment of fully plastic materials and complex structural configurations that were not amenable to these methods. The impetus was high-performance ship development (hydrofoils and surface-effect ships) for which a need was predictable; that the Navy has not acquired high-performance ships in large numbers has decreased the demand for a formal approach to fracture control. However, the PAAG document can serve as background reference for future planning.

The timing of this document coincided with problems in design of struts and foils for PHM-1. A trial application of the document was afforded through a contract to design a set of struts and foils for PHM using HY-130 steel as the structural material. Problems expected in 17-4 PH stainless steel in the condition used for PHM-1 were not present in the HY-130 system, i.e., the resistance of HY-130 to stress-corrosion cracking, corrosion fatigue and fracture was generally superior to 17-4 PH. The expected problem with HY-130 was general corrosion and erosion, requiring coating technologies which either did not exist or were unproven. Although a detailed methodology was shown for applying fracture control, the vendor paid little attention to initiation and growth of defects saying, quite correctly, that the properties of HY-130 were adequate to obviate these problems at this stage of design, and concentrated more on coatings. In other words, they took advantage of the safe-metal approach.

In the area of machinery (piping, pumps, propulsion systems, etc.), elements of fracture control technology have been the deciding design factors for many years. For example, fatigue design of rotating machinery based on Modified Goodman Diagram methods has been routine. Additionally, linear elastic fracture mechanics concepts have been applied to reach decisions to repair or resume operation of machinery components found to contain defects and, more importantly, for setting maintenance intervals and inspection requirements. Thus, machinery components have been designed and operated using analytical fracture control methods.

Summary

In summary, the Navy currently relies on historically proven concepts to prevent or control crack initiation, propagation, and fracture. By relying on the inherent resistance of the structural materials to these failure mechanisms and on proven design methods, the need for very accurate knowledge of loads, stresses, defect sizes, etc., has been avoided. One of the penalties for this is cost-related, in that the true limits on structural performance are not sharply defined. For this reason, adequate materials and fabrication methods that are less expensive than those utilized may be rejected. Another penalty involves an effective limitation on the maximum strength of materials that can be used and thus can adversely impact performance for weight-critical vehicles. Either method of fracture control - safe metal or linear elastic fracture mechanics - involves cost; the most significant difference is in the level of technology needed to implement one or the other.

REVIEW OF CURRENT PROBLEM AREAS

The direct approach was employed to identify current fracture-control problem areas; that is, the technology users in the Naval Sea Systems Command were asked their views on the subject. Visits by personnel from the Naval Research Laboratory and the David W. Taylor Naval Ship Research and Development Center were made to the appropriate codes in NAVSEA, whose open reception to the idea and complete cooperation are gratefully acknowledged. A listing of individuals contacted in these interviews is contained in

Appendix A. The results can be organized into the general areas of materials, structures and machinery and are reported in that sequence, with some general comments concerning the common threads that run through the responses.

A.   Materials

The primary interest of the materials users is fracture toughness. Three principal areas were cited:

a)   How can "adequate" levels of fracture toughness be defined?

b)   How can Charpy-V toughness values be interpreted?

c)   How to develop a better match between materials properties and design requirements?

These three areas are really a statement of the same situation. Taking them in order, the question of how much toughness is necessary pertains mostly to surface ships, hulls, decks, etc., which comprise most of the steel tonnage used by the Navy. This is a cost effectiveness problem, since a small decrease in the cost per pound could result in significant overall cost reduction. The interpretation of Charpy-V (C_v) values is not a new problem, or one that has a universal answer. Again, it is a cost related problem. Because of uncertainties in the significance of C_v numbers, unless correlated to a more meaningful test, a certain amount of conservatism must be introduced in setting minimum acceptable values, and significant amounts of steel may be erroneously accepted or even rejected by the C_v test. Item C - Better match between properties and requirements - is another way to state the first problem and to extend it to other properties as well. For example, because of the design methods that govern the safe-metal approach, structures may be over-designed and material with properties higher than necessary are often used. The entire problem revolves around the need for better definition of materials requirements and better methods for characterization of materials so that the cost of construction and maintenance can be reduced. This is neither a simple materials problem nor a simple design problem, but one involving both disciplines.

A lack of adequate data on new materials or fabrication processes for which purchase or fabrication specifications are required is a persistent problem. For example, significant changes in weld metal deposition techniques to increase deposition rates are desirable, but the influence on the properties can be significant and is not always well understood. The cost for proving the acceptability of each new alloy system or welding innovation by experimental means is, in most cases, prohibitive. Unless the benefit to be gained is substantial, changes in approved practices must be either accepted with insufficient data or disallowed.

An area of long standing concern is that which can be called "defect characterization." The problem is the establishment of soundly-based criteria for acceptance or rejection of base materials and weldments which have some

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form of defect - slag inclusions, cracks, porosity, undercuts, lack of penetration, etc. Not all defects degrade the material or weldment sufficiently to prevent its use. It is considered by the materials codes that some of the existing criteria are based on a "worst possible case" condition; i.e., many defects are treated as sharp cracks, when in fact they are not, which may lead to rejection of otherwise good material or weldments causing an increase in overall cost.

The introduction of new nonferrous metals systems from development to the point where procurement specifications must be written represents a problem area. The problem is that most specialized materials cannot be directly substituted for steels. These materials are so expensive that they can only be considered for those applications that cannot be accommodated using other materials. The cost of model tests in large enough numbers to adequately define performance characteristics is prohibitive, so that the only approach is to define the best attainable properties of the materials and write procurement specifications to assure that these properties are, in fact, obtained. This requires some educated guesses as to what properties will be guaranteed by an industry reluctant to offer such guarantees.

B.   Structures

The principal concern of the structures codes as regards the application of existing analytical methods for fracture control is that they do not go far enough. Specifically, a large part of the technology does not apply to existing hardware design, and the technology that does apply has in most cases not been sufficiently developed. Major items of concern are :

a) Defect characterization (repair or tolerate)

b) Minimum fracture toughness requirements for specific structures

c) Significance of K_{Iscc} for structural design

d) Correlations of laboratory specimen data to structural response

e) Formal approaches to use of FCT

Defect characterization, as defined in a previous section, is in effect the "bottom line" of fracture control technology. The question has two parts: 1) how to set attainable flaw-size inspection limits to match maintenance operations and 2) how to decide with confidence whether or not a known defect can be tolerated. Both aspects are cost-effectiveness problems. The technology exists to inspect most structures for defects of reasonable type and size. However, the cost of complete inspection and repair of all defects is often prohibitive; therefore engineering judgment or simple workmanship standards rather than rational criteria often become the deciding factor for answering these questions. A better developed technology aimed specifically at the problem of defect characterization would enormously benefit structural designers as well as shipyard operations.

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Minimum fracture resistance requirements are a long-term problem to ship designers. Navy practice, particularly in submarine structures, is to require the highest toughness of basic construction materials that can be obtained at a reasonable cost following the safe-metal philosophy. A more exact knowledge of toughness requirements could lead to reduced materials and construction costs. The scope of the problem to date has prohibited general solutions. For example, at low temperatures, HY-80 steel has toughness superior to other carbon steels and is therefore used for keel plating and shear strakes to arrest propagating cracks that might originate in mild steel hull plates or decks. Proven methods to design such crack arrestor schemes so as to minimize the amount of HY-80 required are not available, and the crack arrestors may be over-designed. Similarly, the fracture performance of less expensive materials, which could be substituted for HY-80 in crack arrestors, is not known in sufficient detail to warrant their use with confidence. Again, this is an instance where the safe-metal approach works, but better information on material performance and structural requirements could result in cost savings.

A problem area of concern to structures is the stress-corrosion-cracking technology and its significance to structural design. In particular, the parameter K_{Iscc} is used to measure the resistance of materials to stress-corrosion cracking, and methods to translate these data to predict conditions for the onset of crack growth under conditions of static loading have been verified in the laboratory. However, there are few, if any, naval structures with purely static loads, which renders the direct applicability of K_{Iscc} data questionable. The situation amounts to a technological void which will require some development before K_{Iscc} or another parameter can be used with confidence.

The lack of verified approaches to transition from specimen data to structural response is the largest obstacle to implementation of analytical fracture control methodology in the Navy. Most of the crack initiation, crack growth and fracture methodology have an empirical base, i.e., all small scale laboratory-specimen work is based on the assumption that material samples are accurate models of the structure. The lack of data on models large enough to realistically represent structures represents a void in the technology base. For example, crack growth rates in a welded complex structure cannot be predicted without reasonably accurate knowledge of the influence of geometry and residual stresses on stress intensity - (K) calculations. In small specimens and in simple larger element specimens, the ΔK approach to fatigue crack growth has been demonstrated successfully. The missing links are more complex models and suitable analysis methods to predict crack growth characteristics of real structures, including the effects of a salt-water environment and spectrum loading. The same void is present for all of the parameters that make up fracture control technology, though for a lesser extent as regards fracture because considerable work has been done on this aspect.

Most of the above "problem areas," which can be considered deficiencies in the technology, can be summed up in the last cited item - definition of a formal approach. The best of all worlds for designers is the "cookbook" approach. Since fracture control is only one facet of a complex, interwoven set of variables which make up the design of a ship, the simplest way to transition

the technology into design is through design documents, such as Design Data Sheets or Structural Design Manuals. On the other hand, the fracture control area involves many facets which are already codified and many which defy this process. A review of industries other than military shipbuilding reveals many of the intricacies that are involved in formalization of complex technologies. While it is not likely that fracture control technology in its entirety will ever be reduced to such documents for military ship design, it will be quite useful to have some of the more important aspects contained in standard design documents.

C.   Machinery

Of the three technical areas where fracture control technology can be utilized, the machinery area has made the most effective use of the analytical concepts available. This is by virtue of the applications involved. Rotating machinery components have been designed primarily on the basis of fatigue strength for many years, while other components, such as the PHM WYE duct and aircraft carrier steam receivers, lend themselves well to fatigue crack initiation analysis and fracture design. Because most machinery components are much more amenable to accurate prediction of loads and environments than are complex welded structures, the potential benefits of fracture control technologies are primarily cost savings and increased reliability. The major problem areas cited by the machinery codes are:

a)   Lack of materials property data as inputs to fracture control analysis

b)   Defect characterization

c)   Need for documentation of available methodology

A lack of adequate banks of materials property data for many of the materials used in machinery systems is a major impediment to improvement of reliability and/or performance. It also impedes the introduction of new materials and the application of fracture control technology. Data are expensive to acquire, particularly fatigue-crack growth and fatigue-crack initiation data. It is necessary to base new designs on statistically significant bodies of material properties data; the systematic gathering of the data bases is often impossible because of cost. Thus, there is considerable reluctance to replace pumps, piping systems, etc., that have worked in the past and will probably continue to work in the future. However, in the development of new systems, such as waterjet propulsers, that require new materials, the Navy must rely on the best efforts of contractors until these systems are proven in service.

Defect characterization is also a problem with machinery systems. Scientifically based accept/reject criteria for flaws are nearly non-existent. Additionally, it is difficult to convince ship operators that cracks or other defects in some components are acceptable for a given time period or number of operating cycles. It is often easier to replace or repair components than to prove, by any means, that a flaw does not hamper performance or reliability. Retirement-for-cause criteria have yet to be developed. While a better technology for

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defect characterization might provide some short-term solutions to existing problems, its real benefit would have to be in the longer term, particularly in influencing acceptance standards and determining maintenance intervals for new machinery systems.

Formal documentation of fracture control principles in a format that could be used by practicing engineers would be helpful to machinery system designers. Other than fatigue-crack initiation design procedures contained in general codes, such as the ASME Codes, there are no formally documented procedures available for direct use. As with materials and structures, there are no resident fracture technology specialists in the machinery codes, so in the rare instances where fracture mechanics expertise is required, laboratory specialists must be consulted. This works for the present systems, but in the absence of readily available, documented standards for design based on reliability, little or no improvement of machinery systems resulting from application of fracture control technology seems probable. Formal documentation of currently available fracture contol technology can reverse this trend.

D.   Common Problem Areas

There were two related problems that were common to all activities interviewed; these were defect characterization and cost reduction. Defect characterization was the most often cited; the particularly strong implication was that many of the defect tolerance standards currently used are unrealistically severe. One source of this problem is that inspection methods have improved greatly over the last decade so that more flaws are being found. The focus of fracture control technology is exactly on that question, i.e., the capability to predict behavior of defects. Therefore, while the implementation of fracture control technology could alleviate some of these problems, there is a general reluctance to place a great deal of confidence in the technology. In other words, there are insufficient test data on structural models to warrant a change in attitude toward defect tolerance.

The present outlook of the Navy materials and design community appears to be that the biggest potential improvement offered by fracture control technology is cost reduction. The safe-metal approach has been proven to be an effective way to design and operate ships; however there are areas where potential cost reductions at no sacrifice in performance are deemed desirable and possible. Except for a small number of applications where the necessity to deviate from standard methods precludes use of safe metals, the areas for improvement can be divided into two groups: establishing more meaningful minimum values of required material properties and establishing rational criteria to accept or reject defects.

Establishing meaningful minimum materials properties and devising methods to assure the quality of both materials and workmanship is essential to fracture control. Perhaps the most difficult problem in the safe-metal approach is to define a minimum value of fracture resistance of the structural material for a particular application when analytical methods to determine this do not exist. Many of the problems expressed as "how much toughness is

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enough" derive directly from the methods used to characterize materials and from the inexact state of knowledge of operating loads and other service conditions that structures are expected to withstand.

Of the factors included in fracture-control technology, fracture remains the most important single failure mode considered in ship design. A great deal of research and development effort has been expended on means to prevent fracture. A plethora of tests to discriminate between materials has been developed; each has its particular good and bad points. The most widely used, but least discriminating of these, remains the Charpy V-notch test. This test is preferred by many users because it is small, inexpensive, and well institutionalized. However, it has no direct quantitative engineering value and must be correlated with more definitive tests or service experience for use in setting minimum quality control standards. Furthermore, it is not consistent from one family of materials to another or even within a generic materials family, such as steels. Basically, Charpy V-notch fracture toughness values are subject to broad interpretation, leading to inconsistent usage throughout the industry.

Other material tests that have been used to discriminate between materials on the basis of fracture resistance include Drop Weight NDT, Explosion Bulge and Explosion Tear, Dynamic Tear, K_{Ic} and more recently, J integral. Each of these has an intended purpose and fits into either the material characterization or structural element category. It has been generally recognized that screening of structural steels on the basis of shelf performance (maximum fracture resistance at minimum temperature) can be best accomplished for Navy purposes by Dynamic Tear test methods. However, the industry standard (and the Navy standard) remains the Charpy V-notch test with the acceptance criteria determined by correlation methods as cited above. Nevertheless, recent moves to include a Dynamic Tear test specification for procurement of HY-80 and HY-130 plate and HY-130 welds suggests that this situation may be changing.

REQUIREMENTS FOR USE OF FRACTURE CONTROL TECHNOLOGY

Given the size of the problem to be addressed by either method of attaining protection from crack initiation, crack propagation, and fracture for the entire fleet of Navy ships, the only logical approach is that of safe-metal where it can be applied and fracture control where safe-metal is not adequate or where sufficient benefits can be attained. Certainly there is no justification for changing a proven system without a considerable gain; for this reason, to suggest a blanket application of analytical methods of fracture control to ship hull design would be absurd. The safe-metal approach is not perfect; probably its greatest shortcoming is the lack of a clear demarcation of its boundaries of application. On the other hand, the principles of fracture control technology are not completely developed and the proof of the applicability of many of these principles toward solution of specific Navy problems is nearly non-existent.

By far the largest gap in completing the ship designers repertoire of methods for dealing with crack initiation, crack growth, and fracture is the lack of clearly-defined criteria for choosing either method. Presently, the Navy attitude is to use the safe-metal approach until it is shown that it is inadequate. Fortunately for the Navy, there have been few instances where the safe-metal approach hasn't worked; the only significant problems stemming from non application of safe-metal methodology are the PHM struts/foils and the controllable-pitch propeller. Among the lessons learned from these problems is that the use of analytical methods in the material selection and design phases of the project is far more effective than use of the technology to explain the reasons for the problem and to devise remedial measures. For this reason, the Navy should move to establish a mechanism to screen out these potential problem areas and to establish a methodical approach to deal with them early rather than late.

The review of Navy problem areas in application of fracture control technology produced some insights into directions for future development in the technology. The present situation appears to be that while the developers of the technology have confidence in the viability and value of analytical methods, the users do not. For the present generation of ships and submarines, the need for analytical methodology on a large scale does not exist and, until there is a change in construction materials and/or performance goals, the situation will not change. However, to meet needs of future ships with enhanced performance (deeper diving, faster, lighter, etc.), proven fracture control methods and the means to implement them on a large scale will be necessary. For example, a proposed titanium king post for the PHM was rejected largely because of lack of information on material properties and a lack of a standardized approach for assessing the risk of using this component.

The technical requirements can be summarized in the following three steps:

1. Develop criteria for invoking analytical fracture control technology.

2. Develop standardized methodology.

3. Develop the technology for use in real structures.

Criteria for determining when analytical fracture control methods are appropriate would best take the form of a trigger mechanism in the early phases of design. Use of new materials or materials with key properties known to fall below minimums (e.g., fracture resistance), new configurations with unknown fatigue characteristics and non-redundant structural members or machinery components that are critical to the survival of the ship are possible situations which should require consideration of implementing a formal fracture control plan. The establishment of a clear set of conditions where fracture control technology should be applied must be the responsibility of the users of the technology.

The lack of standardized methodology for application of existing technology and the lack of supporting documentation has hampered previous attempts to use what is known. In the areas of fatigue crack growth and fracture, standardized methods that apply to the problems normally encountered by the Navy have been slow to appear. The difficulties in a simple data acquisition excercise involving crack growth rates in seawater have proven to be substantial and have required that a Navy standard method of test be established. Standard methods for life prediction for typical structural components will probably be more difficult, but they are absolutely necessary.

Efforts to establish connecting links between laboratory test results and real structure have been minimal because of the cost associated with testing models. If one remembers that most of fracture control technology is largely empirical, the importance of the connecting links becomes obvious. In the aerospace industry, it is common practice to test a series of models of increasing similitude to the finished product, ending with a full-scale article test, to confirm life predictions of critical components. The economics of producing large numbers of identical aircraft make this practice acceptable. This situation does not apply to the Navy since few ships are identical and the approach to attaining adequate life is different. To use fracture control technology effectively, however, sufficient information concerning how laboratory defined properties and analysis methods apply to specific structures must be generated.

One method of attaining the objectives outlined in the above is the application of analytical fracture control technology to hardware systems that are currently problems or to hardware items where a considerable gain in performance or a cost reduction could be realized. Fracture control technology is being applied to the controllable-pitch propeller problem and efforts are ongoing to develop a better understanding of crack arrestor on surface ship hulls. There are other areas where the exercise of this analytical approach could benefit fleet ships, e.g., use of titanium for PHM strut/foil components.

REQUIREMENTS FOR IMPLEMENTING A DETAILED FRACTURE CONTROL PROCESS

The majority of naval structures has not utilized a formal fracture control plan; use of the safe-metal approach, time-proven design and fabrication procedures, and redundant structure where possible has eliminated the need for detailed consideration of crack initiation, crack growth, and fracture. By these mechanisms, fracture control has been woven into the entire design process and cannot be extracted and examined as a single entity. However, there have been instances where this standard methodology was not adequate, and the development of advanced ships will probably generate more. As discussed earlier, the items which trigger the need for application of analytical fracture control methods are the use of materials with strength levels significantly higher than the service-proven standard construction materials, a departure from traditional construction methods, or a need to control unforeseen maintenance costs. Thus, the distinction of the two approaches to fracture control (formal or informal) becomes one of level of detail and whether the fracture control plan is considered as an individual item.

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In view of past experience, the need for a formal fracture control plan has appeared after the fact when problems with hardware have occurred, e.g., PHM struts and foils and the controllable-pitch propeller. The Navy does not have a formal procedure to screen out potential problems nor a standard method of dealing with such problems where they occur. There is a real need for a well-defined approach to the formal application of fracture-control technology. The following four steps comprise a possible outline of the Navy part of such an approach.

1. Decide where a formal fracture control plan is necessary

2. Define what factors are to be included

3. Define what is acceptable in fracture-control analysis

4. Establish a mechanism for government review of contractor efforts

Implicit to the above four steps is a distinction between Navy inputs and contractor inputs to a fracture-control plan. These four steps assume that the Navy defines the need, the operational requirements, and what it will accept from the contractor, as well as establishing a mechanism to review the contractor products. This follows the practice currently used in NAVSEASYSCOM for monitoring contractor efforts in all areas. The contractor must know what is expected of him and what is acceptable practice.

The Navy must define the problem, while the contractor must produce a satisfactory solution. The Navy determines the requirements of an acceptable fracture control methodology to be used by the contractors. The contractor must provide a satisfactory fracture control plan and perform the analyses and tests needed to implement it. This includes generating material properties, fracture and crack growth calculations, assembly or prototype tests, and design confirmation. Within this process, the Navy must decide on the level of effort (on a criticality/cost basis) necessary. For example, the Navy must determine the amount of materials data available and the relevance of this data, and then determine the minimum amount of additional data the contractor must furnish.

For these reasons, requirements for implementing current fracture control technology in the design and operation of naval systems center around the documentation required of all parties involved in the fracture control process. Documentation is necessary to quantify fatigue, flaw growth, and/or fracture analysis or design. The level of detail in the analysis or design is dependent upon the part being addressed (its intended use and criticality) and the information available for analysis. For example, the safe-metal approach requires very little documentation other than material test results and conditions. In the sense of quantification, the safe-metal approach is a relative design approach to fracture control. The fracture criticality of the part or structure being addressed is not quantified, and there is no assessment of probability of failure. Therefore, requirements for implementing a safe-metal approach can be simply stated as documentation of material test data that adequately evaluate the fracture resistance of the material, in the environment

and condition intended. The use of such standardized test methods as the dynamic tear test (3) in the design of a naval structure would be an example of fulfilling requirements for safe-metal fracture control. In contrast to the safe-metal approach, a fracture control plan approach would require extensive documentation. An example is Boeing's fatigue and crack growth analysis of the strut/foil system of the PHM.

Navy-provided documentation is required to define the expected or design operating conditions of a particular ship or submarine and how those conditions would affect the fracture control of all critical components. Included in those operating conditions are environment, loads (or stresses), and periods of operation. Included in the environmental conditions should be the media in which any critical component would be required to operate, such as seawater, air, fuel, corrosives, salt water spray, etc., and the approximate lifetime exposure to these detrimental conditions. Elevated temperatures and the time at these temperatures should also be included for those components required to operate at temperatures where material performance is affected. Loads or stresses should include limit or maximum conditions for fracture analyses, and lifetime cumulative conditions for fatigue and flaw growth analysis. If lifetime loads or stresses are not readily available, then expected operating areas, sea states, maneuvering conditions, etc., which can be used to generate loads spectra should be provided, along with any appropriate transfer functions that will translate these operating conditions into loads or stresses. Operating times are another crucial input, since they will define the boundaries of any flaw growth analyses. Operating times in various sea states or load generating levels is required, as well as total operating time and planned operating times between major and minor overhauls. The latter are required for fracture-safe design of systems which cannot be designed to last the full system life. Intended operations of ship systems have dramatic impact on the ability to design for fracture safety. It is imperative that accurate predictions be made early in concept or preliminary design.

In the contractor's phase, quantitative assessments of fatigue and fracture performance can be divided into four categories: material characterization, nominal structural performance requirements (calculations), fatigue and fracture assessment, and design confirmation. The level of detail required in each of these areas is dependent upon the criticality of the component in question, the availability of sufficient data and constraints of the design schedule. This level must be determined by the Navy and specified in the contract.

Material characterization includes the usual mechanical and physical data such as tensile and compressive properties, density, etc., as well as dynamic mechanical properties, and fracture performance characteristics. Dynamic material properties are required to assess nominal structural performance under impact and shock loading conditions. These properties include strain-rate effects on modulus, yield and ultimate strength. Materials property data banks should include all of the necessary properties in statistically significant quantities. Fatigue data should be of sufficient quantity to generate a modified Goodman diagram, or its equivalent, with reasonable confidence at all stress ratios and including a range of K_T's from 1.0 to 3.0. The major problem

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associated with past fracture performance data is that they were generated under conditions that did not properly reflect the as-fabricated and service conditions of the part involved. It is imperative that both test conditions, i.e., environment, loading rate and direction, etc., and materials conditions, i.e., heat treat, welds, etc., be exactly as they would be in service. If test conditions are different than service conditions, the effect on material properties must be quantified, not merely estimated. For example, since there are presently no standardized test procedures for corrosion-fatigue testing, the contractor must furnish evidence of satifactory performance of components that are subject to corrosion fatigue.

Calculations of nominal structural performance are primarily concerned with detailed stress analysis and joint performance evaluation. Actual joint fatigue notch factors, effective K_T or K_f, are required for fatigue analyses. Usually these values range from 1.4 to 3.0 for welded joints but may be well outside these limits if unusual geometries are involved. Also, internal load paths are important for determining the direction and magnitude of stresses internal to critical joints. In cases where "fail-safe" design approaches are used, then load paths and changes in load paths as a result of structural failure are crucial. For joints where crack growth and fracture are important considerations, it is imperative that exact internal stresses are known for detailed calculations. Eliminating certain modes or conditons of loading because they are not crucial for a static design, as is often done, may not be acceptable for a fracture critical design. A small change in stress level or direction can drastically affect the predicted life of a joint.

Fatigue and fracture assessments include quantitative analysis of a structure's performance and comparison of these analyses to "rational" design criteria. Often these criteria take the form of a statement of the system's design life, time between overhauls, etc. The criticality of a component must also be assessed since this enters into establishing confidence limits and probability of failure limits. Detailed analyses should include fatigue and flaw growth analyses of specific joints under predicted "actual" stress spectra. They should also include fracture analyses under extreme operating loads. Any of various cumulative damage models and flaw growth models can be used for calculations provided that detailed rationale is provided to explain the applicability of the chosen models. It is also imperative that the material constants used in any detailed analyses be derived from truly representative tests. Additionally, appropriate criteria must be used in selection of initial flaw sizes. Probability of failure and confidence limits should be calculated for each analysis to allow the Navy some flexibility in deciding whether a part is acceptable or not. Currently, there is not a standardized format for presenting fatigue, slow crack growth and fracture analyses. This is one area that requires immediate attention since past attempts at providing detailed analyses have been somewhat confusing.

The last aspect of requirements for implementing fracture control technology is design confirmation. Design confirmation is the testing of components or systems under design conditions to verify the design life calculations. The complexity of the tests involved depend upon test and service

experience with the types of structures and joints involved and the final life margin of safety. For example, a mild steel bulkhead attachment to a high tensile steel main deck on a destroyer type ship would require little or no design confirmation since the experience base has shown no fracture critical problems in this area. However, a hydrofoil kingpost, made of titanium, which must undergo a lifetime of 10^8 cycles in a salt-water environment, whose failure may mean loss of the ship and which has a design life margin of .01 would require extensive design confirmation testing, probably including full-scale testing. The level of design confirmation is a subject of much debate under today's conditions of constrained budgets. However, the issue must be addressed and the question of "how much testing" must be answered in quantitative terms if fracture control technology is to have a serious future in naval ship and submarine design.

SUMMARY

The technology currently used to control the initiation and propagation of defects and to prevent catastrophic fracture in the design and operation of Navy ships and submarines was reviewed. The background of development of this technology was also reviewed and an assessment of the major difficulties encountered by ship designers was compiled. Several factors emerged from the details of these reviews.

a)   Except for extremely rare instances involving specialized material/ structure combinations, fracture control is accomplished by selection of structural materials that can tolerate defects at severe operating conditions and by the use of experience-proven weld joint details. This approach, called the "safe-metal" approach, nearly eliminates the need for detailed, analytical consideration of fracture and crack initiation and growth in the design of ships and submarines. Since it is a proven, cost-effective method, use of safe metals for Navy shipbuilding will probably continue indefinitely as the means to ensure structural integrity. A distinction is drawn between structural integrity, which involves the entire process of naval ship and submarine design and includes all of the fitness for service considerations, and fracture control, which involves the technology for detailed, analytical consideration of crack initiation, crack growth, and fracture.

b)   The analytical approach to structural design founded in linear elastic fracture mechanics has applicability for the specialized cases where safe metals cannot be utilized. Fracture mechanics methods can be utilized for assessment of the sensitivity of materials to crack growth due to corrosion-fatigue and stress-corrosion cracking. The connecting link between simplified tensile-test models and the behavior of cracks in complex welded structures has not been sufficiently established to instill the confidence necessary for design use of this technology.

c)   Problem areas in use of the safe-metal approach were predominately cost related. Specification of minimum materials properties is the foundation of fracture control implemented in this manner. The precise values of

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fracture resistance necessary for fracture prevention, for example, defy definition. The lack of quantified fracture resistance requirements results in the use of metals with toughness levels higher than necessary and a concomitant increase in costs. The second cause of high construction and operational costs is repair of defects. Improved NDI methods find many defects; not all of these degrade structural performance. Identification of benign flaws and rational methods for analysis to prove their safety, if implemented, could save significant costs.

d) The Navy does not currently have a standard method of identifying and solving crack growth and fracture problems that are not encompassed by the safe-metal approach. Detailed fracture control methods must be used to account for fatigue, crack growth, and fracture in structures or components where the useful life is defined by these processes. Successful implementation of such a plan depends on cooperation between Navy and contractor; the key is that each knows what is expected. Specifically, the elements of such a fracture control plan that are incumbent on the Navy are:

1. Decide when a formal fracture control plan is necessary.

2. Define factors to be included.

3. Define acceptable analysis methods.

4. Develop the mechanism for continuing Navy review.

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APPENDIX A.

NAVSEA personnel contacted for

review of current problem areas

Structures	Machinery	Materials
P. M. Palermo	M. G. Dhawan	R. A. Manley
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